T]] E PROPOSED NASA 1')'ROS110CK '1'11S'1' CRITERI A STANDARD - I'AR'I'1

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The National Aeronautics and Space Administration has traditionally left the task of specifying design and test criteria to each of the several NASA Centers. Faced with the wide variety of resulting criteria used for resolving similar or identical problems, the NASA Office of Chief Engineer initiated a program to develop consistent NASA-wide standards if the various NASA Centers could agree to a set of common requirements. Considering the very wide variety of approaches used throughout NASA and the aerospace industry for coping with pyrotechnic shock problems, the development of a NASA Pyroshock Standard is a formidable task. This paper attaches the second draft of tile Subject Standard, and is based on the comments received from NASA reviewers and pyroshock practitioners to the first draft sent to approximately 60 personnel. This draft has been sent to the NASA Engineering Standards Steering Council for their review and concurrence, prim to its submittal to the NASA J Engineering Management Council for their approval and eventual (distribution.

1.0 INTRODUCTION

Pyrotechnic shock or pyroshock is the transient response of structural elements, components, assemblies, subsystems and/or systems to loading induced by the ignition of pyrotechnic (explosive- or propellant-activate[i) devices incorporated into or attached to the structure. For aerospace applications, pyrotechnic devices are generally used to separate structural subsystems (e.g., payloads from launch vehicles), deploy appendages (e.g., solar panels), and/or activate on-board operational subsystems (e.g., propellant valves) [1-3]. In certain cases, the pyrotechnic loading may be accompanied by the release of stored energy due to structural preload, or by impact between structural elements as a result of tile explosive or propellant activation.

Current spacecraft design often utilizes numerous pyrotechnic devices over the course of a mission. Many fright hardware failures have been attribute.(i to pyroshock exposure, some resulting, in catastrophic mission loss [4,5]. Specific examples of pyroshock failures include cracks and fracture in crystals, ceramics, epoxies, glass envelopes, solder joints and wire leads, seal failure, migration of contaminating particles, relay and switch chatter and transfer, and deformation of very small lightweight structural elements, such as microelectronics [6]. On the other hand, deformation or failure of major structural elements are rare except in those regions close to the source where structural failure is intended.

Pyroshock is often characterized by its high peak acceleration (300-300,000 g), high frequency content (100 Hz-1 MHz) and short duration (less than 20 msec), which is largely dependent on the source type and size or strength, intervening structural path characteristics (including structural type and configuration, joints, fasteners and other discontinuities) and distance from the source to the response point of interest. Because of the high frequency content, many hardware elements and small components are susceptible to pyroshock failure while resistant to a variety of lower frequency environments, including random vibration. High frequencies also make analytical methods and computational procedures inapplicable for system verification under pyroshock loading. Thus, pyroshock verification is almost always accomplished experimentally [7-9] and pyroshock testing is considered essential to mission success.

Pyrotechnic devices may be divided into two general categories: point sources and line sources [23]. Typical point sources include explosive bolts, separation nuts, pin pullers and pushers, bolt and cable cutters, and certain combinations of point sources and pyro-activated operational hardware (e.g., pyrovalves). Typical line sources include flexible linear shaped charges (FLSCs), mild detonating fuses (MDFs), explosive transfer lines, and certain commercially-available products intended to fully contain explosive and structural debris during and after separation (e.g., Super-Zip™, Sure-Sep™). Point and line sources may also be combined: V-band (Maroon) clamps use point explosive sources which may then allow the rapid release of stored strain energy from a structural preload acting along a line of contact between two structures being separated.

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3.0 REQUIREMENTS

3.1 DEFINITIONS, CONFIGURATIONS AND PRACTICES

3.1.1 Hardware Items and Test Purposes
'1'here arc four categories of hardware items for which pyroshock tests should be performed, when appropriate, as follows:

1. A qualification (Qual) or prototype test is performed on a hardware item that will not be flown, but is manufactured using the same drawing, materials, tooling, processes, inspection methods, and personnel competency as used for the flight hardware. The purpose of a Qual test is to verify the design integrity of the flight hardware with a specific margin.

2. A flight acceptance (17A) test is performed on a flight hardware item, including spare(s), where the hardware design integrity has already been verified by a Qual test. The purpose of a 1 'A test is to detect workmanship errors and material defects that may have occurred during product ion.
3. A protoflight (PF) test is performed on flight hardware when there is no qualification hardware item available. The purpose of a PF test is the same as that for a Qual test, except (hat a P] ' test also satisfies the purpose of a FA test.
4. A development test may be performed on a hardware installation to ascertain environmental conditions, or on a hardware item to determine its susceptibility to an environment, or to verify the adequacy of an analytical model, and/or to eval uate the effects of various environmental reduction measures, usually early in a program.

3.1,2. Levels of Assembly

One or more of the above tests may be performed on a hardware system and/or assembly. Tests performed on payloads, spacecraft and large subsystems arc commonly referred to as system-level tests, whereas those performed on electronic equipment, mechanical devices, components and smal i subsystems arc common] y referred to as assembly-lcvc] tests.

3.1.3 Classification of Pyroshock 1 Environments

Pyroshock environments can be broadly divided into three categories: near-fic](i, mid-field, and far-field. For most aerospace installations, the distinction between these three categories is the magnitude and spectral content of the environment, which depends on tile type and strength of the pyroshock device, the source/ hardware distance, anti the configurational details of the intervening structure, which usually has a strong influence on the hardware design and/or selection. In broad terms, these categories may be described as follows:

1. Near-fic](i is the region sufficiently close to a pyrotechnic source where the structural response is dominated by direct wave propagation from the source. 1 'or very intense sources, such as most line sources, the near-field usually includes struct ural locations within 15 cm (6 in.) of the source (unless there are intervening structural discontinuities, such as joints), often causing peak accelerat ions in e xcess of 5000 g and subst anti al spect ral content above 100 kHz. For less intense sources, such as most point sources, the near-fic](i usuall y includes locations within 3 cm (1 in.) of the source. In a good aerospace system design, there should be no pyrosilock-sensitive hardware in the near-fiel(i, so that no near-field testing will be required.
2, Mid-f ield is the region at a distance from the pyrotechnic source where the structural response is cause.(i by a combination of wave propagation and structural resonances. 1 'or very intense sources, the mid-field usually includes structural locations between 15 cm and 60 cm (2 ft) of the source. (unless there are intervening structural discontinuities), often causing, peak accelerations between 1000 and *5000"* g and substantial] spectral content above 10 kHz. For less intense sources, the. mid-field may extend between 3 cm and 15 cm of the source.
3. 1 'ar-field is the region outside the mid-field where the structural response is dominated by structural resonances, with peak accelerations below 1000 g and most of the spectral content below 1() kHz.

NOTE: References 7, 8, 10-12 combine the near- and mid-fields into one category, which is designated as the near-fic](i.

3.1.4 Test Article Operation

The test article may or may not be electrically powered and operational during the pyroshock event. For assembly-lcvc] testing, power is sometimes applied, even when the hardware is unpowered during the flight event, to detect intermittent failures. For system-level power-on testing, the operational mode. applicable to the flight pyro event is often monitored.

3.2 ENVIRONMENTAL AND TEST PARAMETERS

3.2.1 Environmental Descriptions

Although pyroshock may be characterized as a transient force., strain or velocity [13-16], it is almost always described in terms of an acceleration time history and its derived spectrum:

1. The time history or waveform is usually described in terms of its absolute peak value and its duration. Because vibration and/or electrical mist sometimes occur simultaneously with the pyroshock, the 10% duration, defined as the time between the instant of shock arrival at the measurement point and the. instant that the. waveform has decayed to 10% of the absolute peak value, is sometimes substituted for the total duration [10]. Temporal moments may also be used to characterize the. waveform, including the duration [17]. A typical acceleration time history is shown in Figure 1 [10].
2. One or more of the following spectra may be used to characterize the frequency content of a transient: Fourier, "energy", or shock response (SRS) [18]. The SRS is the one most commonly used for pyroshock environment and test description. *If* the hardware dominant modal properties (including damping values) are known, then the acceleration time history and/or the SRS may be used to compute the hardware response. However, in nearly all cases, these resonant parameters are unknown or inadequately estimated, especially at the high frequencies normally associated with pyroshock, so natural frequencies are usually assumed to correspond to 1/6 octave hand center frequencies over the frequency range of interest, and a constant quality factor is selected as Q=10, corresponding to a fraction of critical damping of ζ=0.05 [10, 19]. In addition, there are several different categoric.s of SRS magnitude, including positive, negative, primary, residual, and maximax SRS [18,20,21]. The latter SRS envelopes the previous four and is the one. most commonly used for pyroshock testing. A typical maximax SRS is shown in Figure 2 [10]. The SRS acceleration is also called the maximum or peak absolute response. acceleration.

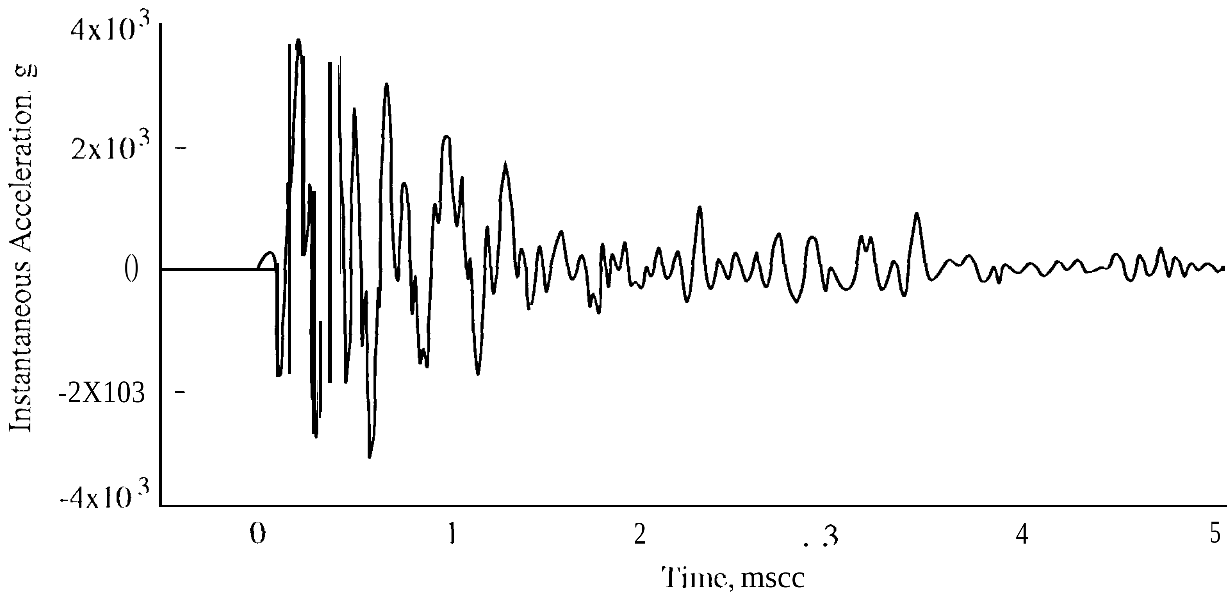

Figure 1. Typical Pyroshock Acceleration Time History

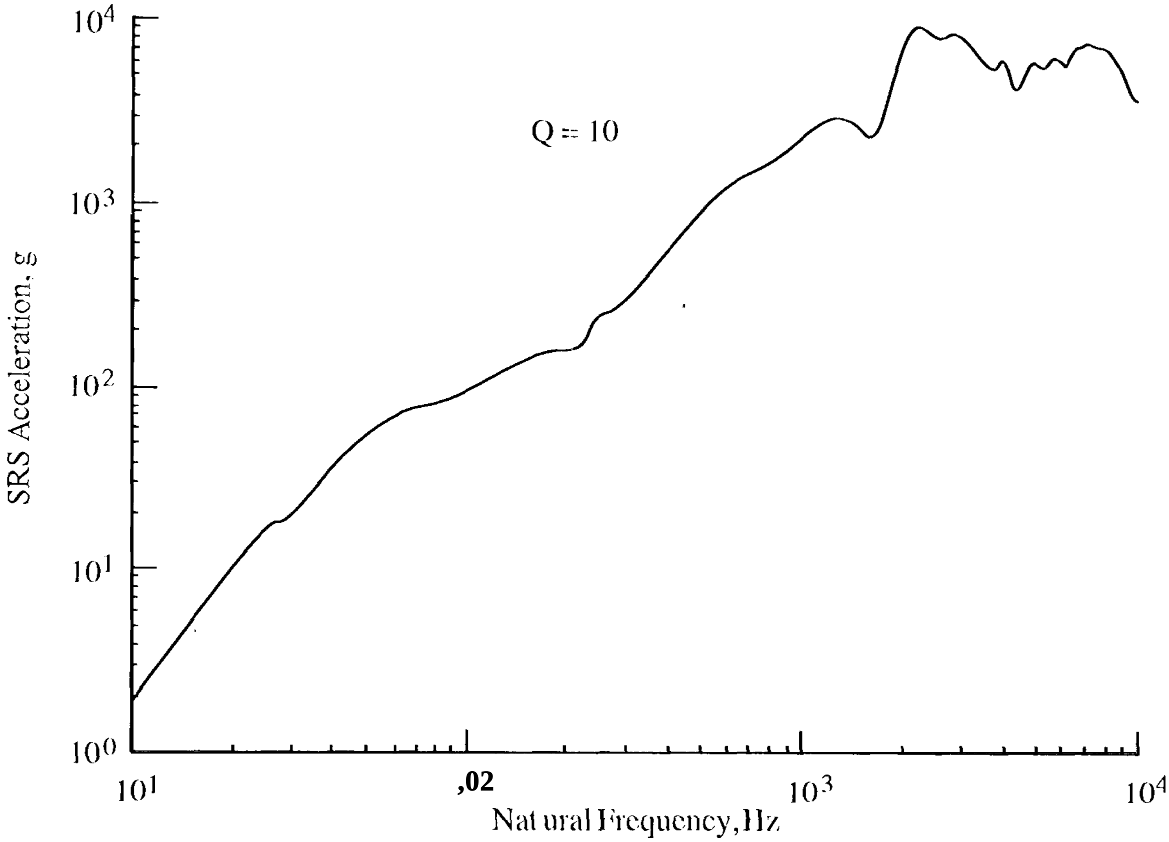

Figure 2. Typical Pyroshock Maximax Shock Response Spectrum (S1<S)

3.2.2 Maximum Expected Flight 1 environment

All ~~ylc~tcclllllic.test conditions should be based upon the maximum expected flight or service environment (MEFE), which may be estimated from (a) a transient analysis, (b) an envelope of measured flight or ground test data, or (c) statistical analysis of these measured data. The last alternative is generally preferred when there. are three or more measurements. When statistical analysis is selected, it is common to utilize P95/50 statistics of SRS data, i.e., a 95% **upper** tolerance limit with **50%** confidence, assuming the SRS database is log-normally distributed [22]. However, other statistical parameters may be used [23]. Pyroshock environmental prediction and MEFE determination, which are *critical* to the selection of test criteria, are described in Appendices A and B, respectively.

3.2,3 Test Margins and Number of Applications

Since a Qual test is not performed on flight hardware, it is possible that a Qual test article would pass and the flight hardware fail the same test conditions because of hardware strength variability. Thus, for assembly-level Qual testing, a magnitude margin is commonly added to the MEFE to account for this variability. Furthermore, a fatigue or time-dependent margin is often added. in these cases, a uniform 3 dB margin is normally added to the MEFE across the spectrum, and multiple shock applications are used for pyroshock Qual testing. When performed, assembly-levc] FA testing is commonly conducted at MEFE conditions with one, shock application per axis. Assembly-level PF testing is generally performed at Qual magnitude with one application per axis.

System-level testing is usually performed on flight hardware by firing the. flight pyrotechnic devices, normally after assembly-level testing has been completed. For system-level Qual and PF testing, multiple firings are usually applied to account for firing-to-firing variability, whereas for system-level FA testing, only one firing is normally used. The test purpose is to identify workmanship errors and/or material defects without contributing a significant amount of additional damage to the hardware prior to flight.

3.3 TEST METHODS AND SPECIFICATIONS

3.3.1 Pyroshock Test Rationale

The decision to perform or omit pyroshock testing should be based on (1) the known ruggedness or robustness of the hardware, (2) the relative severity of the pyroshock environment compared to lower frequency dynamic environments, such as random vibration, and (3) the range of dominant hardware resonances relative to the anticipated spectral content of both lower frequency and pyroshock environments. For example, the cross-over frequency between random vibration and pyroshock severities may be as low as (a) 100 Hz for near-field pyroshock, (b) 500 Hz for mid-field pyroshock, and (c) 1kHz for far-field pyroshock [4]. Small components are more likely to be susceptible to pyroshock failure in all three categories [6], unless they are protected from the high frequency environment, e.g., by resilient mounts or elements. *If there is a serious question about the hardware susceptibility to pyroshock, then pyroshock testing should be performed.* A pyroshock development test early in the flight program should be useful in determining hardware susceptibility, and avoiding the programmatic consequences of failure during Qual, FA, or PF testing later in the program.

3.3.2 Test Methods and Facilities

Assembly-level pyroshock testing, may be achieved by using one of the following types of sources: (a) a pyrotechnic device [1-3], (b) an impact device comprising, the impact of one structural member (e. g., a hammer) upon another (e. g., a beam, plate, shell, or combinations thereof) [3, 7, 8, 24], or (c) a vibration exciter or shaker programmed to generate short duration transient motion [3, 24, 25]. As described in Section 1.0, there are two categories of pyrotechnic devices: point sources and line sources. In addition, there are a variety of custom or commercially-available impact devices [7-9]. A major advantage of most of the impact devices is their low operational cost and predictable behavior, which is important in planning their utilization, but they have a somewhat limited spectral capability. Electrodynamic and electrohydraulic shakers have the advantage of general availability, low operational cost and known controllability, but they have limited magnitude, spectral and directional capability [26], and have mechanical impedence which is significantly higher than that of most aerospace structures, which often causes dynamic overtest of hardware [27].

A typical assembly-level pyroshock test of an individual test article may utilize any one of the above three source types, plus an intervening structure which usually does not resemble the flight structure. Thus, the simulated shock environment at the test article may intentionally be made more or less severe than flight by using a stronger or weaker shock source (of the variety available), by using a lesser or greater distance between the source and the test article, and/or by changing the. properties and/or configuration of the intervening structure (e. g., materials, thicknesses, and the inclusion, addition or elimination of joints), all of which can have. a significant effect on the magnitude, duration, waveform and/or spectral content of the transient obtained at the structure-test article interface and on the. article response. In cases where there is insufficient data on the dynamic characteristics of the combined source and intervening structure, it may be necessary to perform development testing of the test configuration to ascertain that the desired test environment can be achieved prim to test article installation.

Typical system-level pyroshock tests utilize the flight pyrotechnic device and flight or fiigi]l-like structure between the source and the test article(s). As a consequence, duplication of the flight shock environment can be reasonably achieved, but a test magnitude margin is generally unachievable. 1 lowever, multiple shocks may be applied to account for firing-to-firing variations. in cases where multiple pyro devices arc used during flight, it is common practice. to perform multiple firings of only the pyro devices gene.rating the wofst-case shock environment. The other pyro devices are usually fired onceto verify that they do not generate the most severe shock conditions for any potentially susceptible hardware.

3.3.3 Test Requirements

3.3.3.1 General Requirements

Pyroshock test requirements vary widely and are greatly influenced by the magnitude and spectral content of tile pyroshock environment, which in turn is highly dependent on the distance from the source to the hardware, as well as the characteristics of the intervening structure. Thus, pyroshock test requirements will be provided as a function of source/(cst article distance, namely near-, mid- and far-field as classified in Section 3.1.3 and specified in Sections 3.3.3.2-3.3.3.4.

Pyroshock tests should be analyzed and controlled, if feasible, using a SRS over a natural frequency range from a low to a high frequency limit, unless the measured spectral content shows a somewhat restricted range is adequate. The restricted range may be used if the SRS from an ambient vi bration environment or electrical noise floor equals or exceeds the measured pyroshock SRS (usually occuring near the low frequency limit) and/or the absolute peak acceleration of the waveform equals or approximates tbc measured pyroshock SRS, called the zero peri od response acceleration (usually occuring near the high frequency limit). As discussed in Section 3.2.1, a constant quality factor of Q= 1 () is normally utilized. Multiple shocks are recommended to account for firing-to-firing variations, as discussed in Section 3.2.3.

3,3.3.2 Neat-l~jclci Tests

As discussed in Section 3.1.3, no pyroshock-sensitive hardware should be located within the neat-ficl~i. However, if this recommendation cannot be followed, near-fic](i testing should be required. Bc.cause of the high accelerations and high spectral content found in the neat-fic](i, the lest source and intervening structure is nearly always restricted to tile actual flight pyrotechnic device(s) and flight or flight-like configurations, respectively. In these cases, the pyroshock test requirements should accurately represent the flight environment.. Here, lest margins are often negligible or minimal unless special measures are taken to increase them, e.g., by modifying the structural configuration, and/or by reducing the source-to-hardware distance, or under certain circumstances by increasing the pyrotechnic charge. Use of these special measures usually require a development test program. in other cases, such as high intensity assembly-levc] tests, a simple intervening structure which is not flight-like (e.g., a beam, plate, or shell) may be used bet ween tile pyrotechnic device and the test article [3, 7, 8, 24].

For near-fic](i pyroshock tests, the limits of the SRS natural frequency range should extend from 1 ()() Hz or less to 1 MHz or more, unless the measured spectral content shows a more restricted range is adequate, as described in Section 3.3.3.1. Serious instrumentation problems are usually encountered in the near-field, which are discussed in Section **3.3.4.**

In a few specific cases, a high intensity impact device may be substituted for a pyrotechnic device to achieve the desired peak acceleration *if* it can be demonstrated that the spectral content is comparable at high frequencies, e.g., above 100 kHz [6]. The environmental comparison should be performed in all three orthogonal directions at the structure/test article interface(s). This substitution may be required to satisfy safety concerns or facility legal restrictions regarding the use of explosives. Otherwise, off-site testing should be considered.

3.3.3.3 Mid-Field Tests

A variety of impact devices as well as explosive devices may be used as a test source, as well as a variety of intervening structures for the transmission path from source to test article, to achieve the mid-field test conditions classified in Section 3.1.3. For mid-field pyroshock testing, the limits of the. SRS natural frequency range should extend from 100 Hz or less to 100 kHz or more, unless the measured spectral content shows that a more restricted range is adequate, as described in Section 3.3.3.1. A vibration shaker may be able to achieve a shock magnitude that reaches into the lower portion of the mid-field region, but would probably be unable to achieve the desired mid-field spectral content, since most electrodynamic shakers are unable to provide sufficient excitation above 5 kHz.

Many impact devices and all vibration shakers, together with their intervening structures, are capable of generating controlled transient excitation in a single axis. in these cases, testing will nearly always need to be repeated in the other two orthogonal axes. However, it should be noted that the use of vibration shakers and some impact devices have been criticized for *simulaneously* causing under- and over-testing: undertesting due to uniaxial excitation compared to the triaxial service environment; overtesting due to a massive shaker table. and fixture compared to the service installation, plus accelerometer control in the case of a shaker, without considering the lower structural impedance found in most instillations. Time issues have been previously described for lower frequency sine, transient and random testing [25-27].

3.3.3.4. Far-Field Tests

All of the source types categorized in Section 3.3.2 plus nearly all types of' intervening structure should be usable for far-field testing. The limits of the SRS natural frequency range should extend from 100 Hz or less to 10 kHz or more, unless the measured spectral content shows that a more restricted range is adequate. Single axis shock sources and their intervening structure nearly always require repeated testing in the other two axes.

3.3.4 Data Acquisition

Pyroshock tests are nearly always instrumented for the purpose of environmental evaluation and/or test control. Pyroshock measurements are normally made with accelerometers despite some potentially serious deficiencies. Often in the near-field and sometimes in the mid-field, improperly selected accelerometers break, hard bottom, or saturate under pyroshock loading and/or incorrectly-set signal conditioners may saturate if accelerometer resonances are sufficiently excited [10-12]. If great care is not exercised, these nonlinear responses can make the resulting data invalid over the *entire* spectrum. In most cases, accelerometers should be selected for the anticipated pyroshock environment as well as other conditions, with a higher natural frequency and a lesser sensitivity usually required in the near- and mid-fields [10-12,28]. It has been recommended that the data acquisition system be selected or adjusted so that the maximum anticipated instantaneous signal from the accelerometer is only 10% of the system linear magnitude capability, thus providing a "head room" of 20 dB [29]. In the near field, it is recommended that the accelerometers, and their mounting blocks when used, be attached to the structure with both bolts and special adhesive [10,29]. Inplane measurements usually require mounting blocks and often the special installation of accelerometer pairs to allow for the separation of inplane and rotational responses. Unless care is exercised in their selection, accelerometers located on flexible structure. s may erroneously generate electrical signals caused by base bending [28].

Accelerometer problems can sometimes be avoided by using velocity pickups or, in laboratory ground tests, by using laser Doppler vibrometers instead of accelerometers, although these instruments also have some potentially serious deficiencies [14-16]. Strain gages have also been promoted as replacements for accelerometers, since strain transducers have no resonances but simply respond dynamically with the structure to which they are attached [1,13]. Unfortunately, most aerospace structures are highly non-uniform with large numbers of spatially-varying stress concentrations. Under these circumstances, even small changes in gage location could cause. large changes in measured strain data. In addition, at high frequencies and short wavelengths normally associated with pyroshock, measured strain can also change substantially by a simple change in gage grid size [28].

Once valid electical signals are acquired, data analysis is then required to provide the desired acceleration time. histories and SRSs specified in Section 3.2.1.

3.3.5 Data Analysis
Care must be taken to ensure that data acquisition errors, such as an inperceptible zero shift in an acceleration time. history, do not cause substantial errors in resulting SRS s during subsequ ent data analysis. The Powers-Piersol procedure is recommended for determining the validity of pyroshock data, using simple steps as the single and/or double integration of the acceleration time. history and the comparison of positive and negative SRSs, as shown in Figure 2.1 Even the S1<S computational algorithm may cause an appreciable effect on the resulting spectrum [30-31]. The Smallwood algorithm has been recommended to reduced algorithm-induced variability [32].

3.3.6 Test Conrol Tolerances
Pyroshock tests that utilize pyrotechnic dc.vices have no specific tolerance control. Multiple shocks are often applied to account for firing-to-firing variations, as suggested in Section 3.2.3. For impact dc.vices, control tolerances are often a function of the specific device and its maintenance. When shakers are used for pyroshock simulation, various tolerances have historically been utilized. The tolerances most commonly used in current aerospace practice arc specified for the maximax SRS [1 9]:

Natural Frequency	Tolerance
$f_n \leq 3$ kHz	± 6 dB
$f_n > 3$ kHz	+9/-6 dB

At least 50% of the SRS magnitudes shall exceed the nominal test specification.

3.3.7 Test Tailoring
Sufficient flexibility is provided in this Standard to satisfy the need for test tailoring in most cases. For example, utilization of a pyrotechnic device plus flight or flight-like intervening struct ure, instead of a shaker and some simple fixturing and intervening structure, in a mid- or far-field test should provide the correct driving-point impedance and therefore the appropriate transient force at the structure/test article interface(s), which would accomplish the same goal as force limiting in a random vibration test [27].

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APPENDIX A

PREDICTION OF PYROSHOCK ENVIRONMENTS

There arc three general ways to predict or estimate the response at various locations on a structure induced by a pyrotechnic device, as follows: (a) analytical models, (b) direct measurements, and (c) extrapolations from previous measure.ments.

A.1 ANALYTICAL MODELS

Various analytical models have been developed over the years that are designed to predict, at least crudely, the response of aerospace structures to the transient loads produced by certain types of pyrotechni c devices. Hydrocodes have recently been used to model, in the time domain, the details of the explosive or propellant ignition and burning process, and nonlinear structural deformation and separation using Lagrangian and/or Eulerian meshes, as well as the generation and propagation of structural waves, all of which are necessary for pyroshock prediction [33-35]. Unfortunately, the implementation of hydrocode analysis usually necessitates high labor and computer costs.

Sometimes hydrocode models arc coupled with finite clement method (FEM) or statistical energy anal ysis (SEA) models to transfer the pyroshock energy into the mid- and far-fields. 1 lowever, most FEM models arc restricted to frequency ranges that arc too low to be useful for pyroshock response predictions, or so spatially limited that only simple structural configurations can be accurately modeled. On the other hand, SEA was developed to predict mid frequency vibroacoustic response, modeling the structure in terms of modal groups using spatial and spectra] averaging. These models have been extended to predict high frequency pyroshock response. [36-45]. Thus, SEA is better suited for high frequency pyroshock prediction, sine.c. structural modal density (i.e., the number of structural modes pcr unit bandwidth) needed for spectral averaging is roughly proportional to frequency. In fact, the sparsity or absence of low frequency modes limits S1 :A applications to mid and high frequencies onl y. Because SEA uses spatial and spectra] averaging, it cannot be used to predict pyroshock response at specific locations or frequencies.

At this time, there is very limited experience to assess or recommend the usc of such models. However, if an analytical model is available or has been formulated and checked against pyroshock measurements in the laboratory on specific structures with pyrotechnic, devices of interest, and has been found to produce reasonably accurate results, then that model can be used to make prelim-inary pyroshock predictions. However, all such predictions should be verified and updated as soon as actual pyroshock data become avail able.

A.2 DIRECT MEASUREMENTS

in many cases, direct measurements can be made of the. responses at critical locations on the spacecraft structure induced by pyrotechnic devices, either in flight or in the laboratory. in either case, the measurements should be acquired and analyzed in accordance with the recommended practices detailed in [1 ()-1 2].

A.2.1 Measurements on the Vehicle in Flight

For some spacecraft, more than one assembly are manufactured because the same spacecraft design will be used for more than one flight. in this case, measurements may be made on the first flight of that design to establish the response of the structure at critical locations due to all flight pyrotechnic events. The advantage of this approach is that it provides the most accurate pyroshock predictions for later flights of that design. The primary disadvantages are (a) the procedure applies only to updating predictions after the first flight and, hence, cannot be used to establish initial test requirements for the spacecraft or its components, and (b) flight pyroshock measurements are expensive to acquire.

Pyro devices are usually dc.signed or selected to generate more than enough source energy to cause structural separation. The excess energy normally causes a shock or blast wave in the atmosphere or vacuum adjacent to the structure, with the wave magnitude increasing with excess energy and static pressure. However, for smith amounts of excess energy, the separation process usually controls the pyroshock environment.

A.2.2 Measurements on the Vehicle in the Laboratory Prior to Flight

Certain type.s of pyrotechnic devices can be activated and replaced without doing permanent damage to the space.craf(or its structure, e.g., or(illance-activated valves, In this case, measurements may be made, on the vehicle in the. laboratory prior to flight to establish the response of the structure at critical locations due 10 the activation of these devices. The advantage of this approach is that it can provide a reasonably accurate pyroshock prediction for that specific spacecraft during flight. The primary disadvantages are (a) the procedure allows the determination of the pyroshock environment due only to a limited number of pyrotechnic devices, and (b) it may be expensive to replace the activated pyrotechnic devices and recondition the spacecraft for flight.

If the pyro device generates enough energy to cause an excessive atmospheric shock wave during the laboratory test compared to flight conditions and if this wave is not diverted away from the structure, then an over-prediction of the flight pyroshock environment may result.

A.2.3 Measurements on a Prototype Vehicle in the Laboratory

Some spacecraft programs involve the manufacture of a prototype of the spacecraft design that is used for various laboratory tests, including shock and vibration tests, prior to the. launch of a flight assembly. Because the activation of pyrotechnic devices sometimes alter the spacecraft structure, pyroshock measurements on prototypes are usually made after all other tests are complete. The advantages of a prototype lest are (a) it can provide a reasonably accurate pyroshock prediction prior to the flight of all spacecraft of that design, (b) the prediction is achieved without jeopardizing the strut.tuml integrity of the flight article, (c) no reconditioning of flight hardware is required, and (d) the operability of pyroshock devices and structural separation can be demonstrated following environmental exposure. The primary disadvantage is that the program must provide for the manufacture of a prototype vehicle that wil 1 be available for pyroshock testing. The problem of an excessive atmospheric shock wave is the same as that discussed in Section A.2.2.

A.2.4 Measurements on a Dynamically Similar Structure in the laboratory

If a spacecraft program does not involve the manufacture of a prototype, it may still allow the construction of a dynamically similar mode] of at least those. subassemblies that incorporate pyrotechnic devices, or such a dynamically similar model might be available from a previous spacecraft program, e.g., [24]. The advantages of a test using a dynamically similar mode] are (a) it may provide moderately accurate predictions of pyroshock environments, depending on how close.]y the mode] dynamically represents the spacecraft of interest, (b) the prediction is achieved without jeopardizing the structural integrity of the flight article, and (c) no reconditioning of flight hardware is required. The primary disadvantage is that the program must provide for the manufacture of a dynamically similar model, or an appropriate model must be avail able from a previous program. The problem of an excessive atmospheric shock wave is the same as that discussed in Section A.2.2.

A.3 EXTRAPOLATIONS FROM PREVIOUS MEASUREMENTS

A vast amount of pyroshock data has been acquired and analyzed over the years for many spacecraft programs, both in the laboratory and in flight, e.g., [46,47]. Even though the chits may have been acquired for totally different spacecraft designs and different pyrotechnic devices, at least crude estimates for the pyroshock environment to be expected on a new spacecraft design can be determined by extrapolations from measurements on a previous space.crafl of different design, common l y referred to as t he reference spacecraft. Of course, tile closer the design details of the new and reference spacecraft, tile more accurate tile extrapolations. Also, the most accurate ext rape] at ions are provided when the p yroshocks on t he new and reference spacecraft are caused by the same type of pyrotechnic device.

Ext rapolat ion procedures for pyroshock environments general i y involve t wo primary scaling operations, namely, (a) scaling for the total energy released by the pyrotechnic device [1], and (b) scaling for the distance and structural configuration between the pyrotechnic energy source and the response. location of intc.rest. Sometime.s scaling for the surface weight density of the struct ure is also employed, but such extrapolations usually are not effective because the intense compressive waves generated by pyroshocks are not strongly influenced by surface weight density. Based upon procedures in [46-48], the following scaling rules for source energy and dist ance from the source are recommended.

A.3.1 Source Energy Scaling

Letting E_r and E_n denote tbc total energy released by tile pyrotechnic device on the reference and new spacecraft, respectively, the shock response spectrum at all frequencies is scaled from the reference to the new vehicle by

$$SRS_n(D_1) = SRS_r(D_1)\sqrt{\frac{E_n}{E_r}} \qquad \text{(A.])}$$

where SRS_r and SRS_n are the shock response spectra for the reference and new spacecraft, respectivel y, at the same distance D_1 from the pyrotechnic source. Caution should be exercised in the utilization of Eq. (A. 1) sine.c, in many cases, an excess of source energy beyond that required to cause struct ural separation will not increase the shock transmission, but instead will generate an increased shock or bl ast wave. that wi l l be t ransmit ted into the atmosphere or vacuum adjacent to the stru cture. This excess energy may not be as effective in generating structural response. Thus, when $E_n > E_r$, the application of Eq. (A. 1) may cause an over-prediction of the pyroshock environment. Similarly, an under-prediction may result when E_n <11,.

A.3.2 Source to Response Location Distance Scaling

A number of empirically derived scaling relationships to correct the magnitude of pyroshock environments for distance from a pyrotechnic source to a response location of interest have been proposed over the years [46-48]. One set of scaling curves for typical pyroshocks propagating through various types of structure, as developed in [46], is summarized in Figure A.1. Note the results in Figure A.1 apply to the peak value of the pyroshock response.

Another scaling relationship developed in [48] for the shock response spectrum produced by point sources on complex structures is given by

$$SRS(D_2) = SRS(D_1)\ \exp\left\{\left[-2\times 10^{-5} f_n^{\left(2.4 f_n^{-0.105}\right)}\right]\left[D_2 - D_1\right]\right\} \qquad \text{(A.?.)}$$

where D_2 and D_1 are the distances from the pyrotechnic source to the reference and new locations, respectively, on the spacecraft, and $SRS(D_1)$ and $SRS(D_2)$ are the shock response spectra for the responses at the reference and new locations, respectively. Since Eq. (A.2) predicts an SRS, the results are a function of the SRS natural frequency. Plots of Eq. (A.2) for various values of $\Delta D = D_2 - D_1$ are shown in Figure A.2.

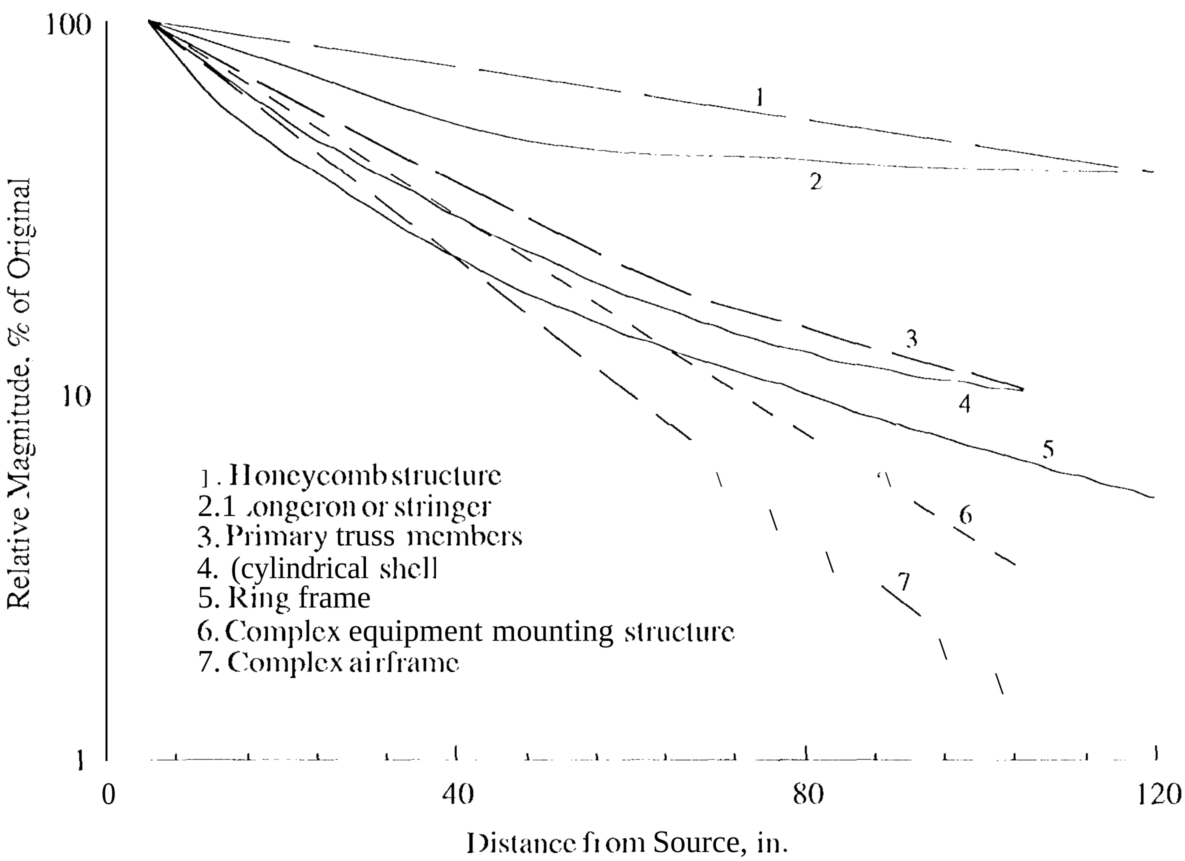

Figure A. 1. Peak Pyroshock Response versus Distance from Pyrotechnic Source.

It is important to note that Eq. (A.2) was derived from pyroshock data produced by a point source on complex structure at sea level, and may not be representative of other sources and structures in *space, as* discussed in *Sections* A.2.1 and A.2.2. Other source scaling rules may be developed from data for sources and structures more like those associated with a specific spacecraft, which may be substituted for the results in Figures A.1 and A.2 [49].

As a final point concerning the attenuation of pyroshocks with distance, there is usually a substantial reduction in pyroshock magnitudes due to transmission across structural joints. Specifically, [46] suggests that the attenuation due to structural joints ranges from 20 to 75%, depending on the type of joint and the manner in which it changes the shock transmission path. Other data for joint attenuation that might be available from prior experience should be used, as appropriate.

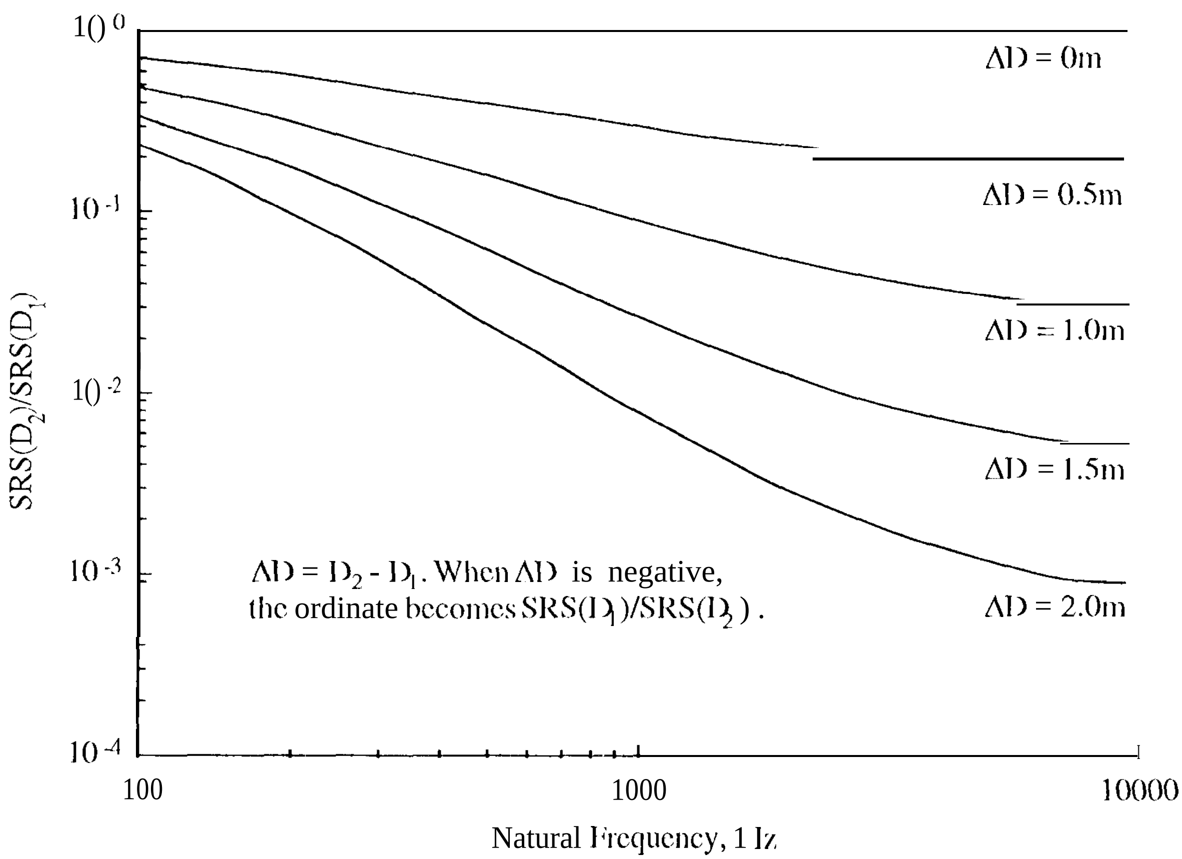

Figure A.2. Correction of Shock Response Spectrum for Distance from Pyrotechnic Source.

APPENDIX B

DETERMINATION OF MAXIMUM EXPECTED FLIGHT ENVIRONMENT

The prediction procedures detailed in Appendix A generally yield the SRS at individual points on the structure that do not necessarily correspond to all the. points of interest in the formulation of pyroshock test criteria. Furthermore, the predictions may be. based upon estimated or measured pyroshocks that do not reflect the potential variations in the pyroshock environments produced by different pyrotechnic devices of the. same type. Hence, it is necessary to convert the predicted pyroshock magnitudes into a single SRS, referred to as the "maximum expected flight environment", that will account for point-to-point (spatial) and event-to-event variations. The computation of the maximum expected flight environment involves two steps, (a) the division of the predictions for a specific pyrotechnic event into groups with similar SRS values, referred to as "zones", and (b) the. selection of a conservative upper bound on the SRS values in each zone, referred to as a "zone limit", which constitutes the maximum expected flight environment for that zone due to that specific pyrotechnic event.

B.1 DETERMINATION OF ZONES

The SRS magnitudes for the structural response.s due to a single pyrotechnic event typically vary widely from one location to another, particularly as the number of joints and/or the distance from the. pyrotechnic source increases. The goal in zoning is to divide the spacecraft structure into regions or zones such that the responses at all points within each zone due to a single pyrotechnic event are reasonably homogeneous, meaning the SRS magnitudes for the responses at all points within each zone can be described by a single SRS that will exceed most or all of the SRS magnitudes at the individual points without severely exceeding the SRS magnitude at any one point. It is also required that the selected zones corrc.spend to structural regions of interest in the formulation of test criteria, e.g., a single zone should include all the attachment points for a single component, and preferably for several components, that must be tested for the pyroshock environment.

The zoning operation is usually accomplished based upon engineering judgment, experience, and/or a cursory evaluation of predicted SRS magnitudes. For example, engineering judgment dictates that frame structures and skin panels should represent different zones, since. the response of skin panels will generally be higher than the much heavier frames. Also, experience suggests that the. structural regions in the near-field and far-field of the pyrotechnic source have widely different SRSs and should represent different zones. Beyond such engineering considerations, a visual inspection of the SRS magnitudes for the predicted pyroshocks can be used to group locations with SRSs of similar magnitudes to arrive at appropriate. zones.

It is assumed that the available SRSs for a given zone are predicted at locations that are representative of all points of interest in that zone. Ideally, this would be achieved by a random selection from all possible. response points within the zone. in practice, a random selection usually is not feasible since the predictions are commonly made before the zones are selected; in fact, the spectra for the predicted responses are often used to establish the zones, as discussed above. In some cases, however, the predictions may be made at those points where a component of interest is mounted. This would constitute a good selection of response points, even though such mounting points might not be representative of all points within the zone. In any case, it is important to assess the locations represented by the available predicted pyroshocks to assure that they are typical of all points of interest in the zinc.

B.2 (X) MPUI'ATION OF ZONE LIMITS

A conservative limit for the predictions at various points within a zone may be determined using any one of several procedures [23], but the procedure recommended here is to compote a normal tolerance limit that covers the SRS magnitudes for at least 95% of the locations in the zone with a confidence coefficient of 50%, referred 10 as the 1'95/50 limit [22]. Specificall y, given n measurements of a random variable x, an upper tolerance limit is defined as that value of x (denoted by 1 .X) that will exceed at least β fraction of all values of x with a confidence coefficient of γ. The fraction β represents the minimum probabilit y that a randoml y selected value of x wi ll be less than L_x; the confidence coefficient γ can be interpreted as the. probability that L_x will indeed exceed at least β fraction of all values of x. Tolerance limits are commonly expressed in terms of the ratio, (10()~)/(1 00γ), e.g., the P95/50 normal tolerance limit represents β = ().95 and 'y= 0.50. in the context of pyroshock predictions, x represents the SRS value at a specific frequency for the response of the. spacecraft structure at a randomly selected point within a given zone, where x differs from point-to-point Within the zone due to the spatial variability of the response. However, x may aiso differ due to other factors, such as variations from one pyroshock to another produced by the same type of pyrotechnic dc.vice. in selecting a sample of predicted SRS magnitudes to compute a tolerance limit, beyond the SRS val ues at different locations within a zone, it is wise to include SRS magnitudes from different spacecraft of the same design, if feasible, so that sources of variability due to location and firing-to-firing arc represented in the measured or predicted SRS values.

Tolerance limits are most easily computed when the random variable is "normally distributed". The point-to-point (spatial) variation of the pyrotechnic-induced responses of spacecraft structures is generally not normally distributed, but there is empirical evidence that the logarithm of the responses from pyroshock as well as random vibration does have an approximately normal distribution [23]. Hence, by simply making the logarithmic transformation

$$y = \log_{10} x \qquad \text{(B.1)}$$

where x is the SRS magnitude at a specific natural frequency of the response within a zone, the transformed variable y can be assume.d to have a normal (ii st ribut ion. For 11 sample values of y, a normal tolerance limit is give.n by

$$L_y = \bar{y} + k s_y \qquad \text{(B.2)}$$

where "y is the sample average. and s_y is the sample standard deviation of the n transformed spectral values computed as follows:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \; ; \quad s_y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (y_i - \bar{y})^2} \qquad \text{(B.3)}$$

The term k in Eq. (B.2) is called the normal tolerance factor, and is a tabulated value; a tabulation of k for β = 0.95 and y = ().50 is presented in 'l'able B. 1, which is taken directly from [22]. The normal tolerance limit for the transformed variable y is converted back to the original engine.c.ring units of x by

$$L_x = 10^{L_y} \qquad \text{(B.4)}$$

To simplify test criteria, normal tolerance limits are often smoothed using two straight lines segments, as found in [7,8].

Table B.1. Tolerance Factors for P95/50 Normal Tolerance Limit

n	3	4	5	6	8	10	15	20	30	50	∞
k	1.94	1.83	1.78	1.75	1.72	1.7(I	1.68	1.67	1.66	1.65	1.64

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